Engineering Mechanics Division
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Summary of Final Technical Report, Project J 6130

Prepared by:

T. E. Waterman

Under Contract No. N00228-67-C-2774
OCD Work Unit No. 2536E

For

Office of Civil Defense
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through:

U. S. Naval Radiological Defense Laboratory
San Francisco, California 94135

Summary of
Final Technical Report, Project J6130

OCD Work Unit 2536E

EXPERIMENTAL STUDY OF FIREBRAND GENERATION

January 1969

OBJECTIVE AND SCOPE

This program involved the experimental study of firebrand generation by various roof constructions when exposed to building fires. The facility constructed and used for this purpose consisted of a reuseable fire chamber 8 ft x 8 ft x 22 ft high, covered with a full scale segment of each roof construction type. Brands produced by each experiment were trapped by a screen enclosure and dropped into a quenching pool. All brands thus collected were sorted, dried, and weighed.

Brand production was studied under the internal pressures generated by the fire in the chamber and with additional pressures generated to simulate larger fires and/or wind induced pressures. Roof constructions included:

1) Wood shingles
2) Two weights of asphalt shingles
3) Roll roofing
4) Cement-asbestos shingles,
5) Built-up roofing,
6) no covering

These were applied to one inch lumber, two inch lumber or 5/16 inch plywood sheathing. Additional variables included roof pitch and configuration (not all combinations were studied).

RESULTS

Tables III, IV and V of the full report are included here to describe the results. These tables consist of a series of bar graphs. Table III contains all experiments with bare roofs and those covered with 235# asphalt shingles (no wind). Table IV contains all other experiments without wind. Table V includes all experiments with wind. The first column of bar graphs on each table represents the weight distributions of brandscollected by sorting screens of one mesh (C), two mesh (M), and seven mesh (F). The second column of bar charts describes the total weights (grams) and numbers of brands per square foot of roof surface. Column three represents an average rate of brand production obtained by dividing the results of column two by the time of active brand production for each fire test.

SUMMARY

The following generalizations drawn from the report are pertinent to the evaluation of the brand producing capabilities of urban areas and to the description of the later stages (transport and host ignition) of brand life.

1) Within the range of induced pressures studied, brands are formed from combustibles that have lost their volatiles and have reached a state of glowing combustion.

2) One inch sheathing produces more and larger brands than 5/16 inch plywood or two inch sheathing. This can be attributed to some degree to the mode of formation. Should the smaller brands prove to be ineffective in spreading fire, this difference will be accentuated.

3) The larger brands from one inch sheathing are generally checkered with deep fissures. The brands thus exist as clustered segments roughly spherical in shape. This would indicate that any increase in the ability of very large brands (greater than about 1-1/2 in.) to ignite hosts is perhaps caused only by their larger area of contact, rather than by greater severity or longer period of burning.

4) Wood shingled roofs (both tight and open sheathing) produce far greater amounts of brands at higher rates than do any bare sheathing or any other combination of sheathing and covering tested.

5) Brand production is greatly increased by high internal pressures associated with wind or the occurrence of a tall fire column below the roof. It is particularly significant that this occurs with built up roofs which are commonly found on large structures. This sensitivity to internal pressure far overshadows the variations produced by the different common asphaltic roof coverings.

6) Addition of an asphaltic covering decreases brand production from one inch sheathing. Intimate contact of the covering (built up roof) decreased brand production at low internal pressures but apparently caused some enhancement at higher internal pressures.

7) Under the range of conditions studied, burning asphalt shingles were found to fly only when fuel was almost exhausted. They were eliminated from further treatment as their effective range was considered to be short, well within the range of fire spread by radiant ignitions.

8) In applying the results presented in the Tables, reasonable approximation should be achieved up to about 0.6 or 0.7 in. H_2O total pressure by linear interpolation along a total pressure scale. It can be noted that buoyancy pressures experienced here were about 75 percent of theoretical under no wind conditions and dropped to about 50 percent of theoretical at wind induced pressures of 0.5 in. H_2O. Similar adjustments should be made for structures having internal subdivision to restrict air flow. Theoretical buoyancy effects (0.011 in. H_2O/ft height) should be used for structures having large undivided volumes. The degree to which wind induced pressure should be applied will definitely require definition of the internal subdivision.

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FIREBRAND GENERATION

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FOREWORD

This is the final report on Contract No. N0022867C2774, Task Order No. 2530(67), OCD Work Unit 2536E (IITRI Project J6130), "Experimental Study of Fire Brand Generation". The program is sponsored by the Office of Civil Defense, Office of the Secretary of the Army through the Technical Management Office, U. S. Naval Radiological Defense Laboratory, Project Monitor M. Gibbons, Code 908C.

This report covers the period from August, 1967 through December, 1968.

Respectfully submitted,
IIT RESEARCH INSTITUTE

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ABSTRACT

Experiments were performed to assess the capability of various roof constructions to produce firebrands when subjected to a building fire. These tests of roof segments were conducted by placing the roofs over the top of a two story fire chamber and, by means of a screen trap and quenching pool, collecting all brands generated. Effects of different building heights (unrestricted fire height) and wind induced internal pressures were simulated by imposing additional pressure on the fire chamber interior.

Results indicate that changes in internal pressures produced marked changes in brand production. Of the roof constructions evaluated, wood shingled roofs were by far the greatest brand producers. Over the range of roofs and imposed conditions studied, the brands produced were of low density and appeared to be in a state of glowing combustion at the time of their generation, or shortly thereafter.

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I. INTRODUCTION

The program described herein is concerned with the experimental evaluation of the capability of various roof constructions to produce firebrands when involved in building fires. Firebrands have been of prime concern to those involved in forestry research for many years. The effect of brands on forest fire spread is well documented and could be quantitized by statistical examination of the records of past burns. Such statistics are not available for urban fires. This is due to the infrequency of large urban fires and the general preoccupation of potential observers with other problems. That brands must contribute to urban fire spread can be deduced by examination of the Wolverton data(1) on fire spread in Germany and Japan during World War II. This information shows apparent fire jumps across spaces much in excess of those that would be expected from calculations of radiant exposure. Unfortunately, the Wolverton data does not contain sufficient detail to relate the fire spread to the prevailing winds or to the time histories of fires in specific structures.

In a more recent study, Kamei(2) developed several curves relating frequency of spot fires and distance using records of eleven conflagrations in Japanese cities. The structures involved were both good brand producers and susceptible brand hosts which led to a very high incidence of spotting. The data is somewhat difficult to interpret in terms of most areas of American cities.

II. DISCUSSION

A. Potential Modes of Firespread

Deterministic assessment of fire spread in urban areas is presently limited to consideration only of fire spread by radiation. Consequently, fire damage or casuality estimates tend to be low. Although past experience shows numerous occasions where urban fires have spread across large gaps, calculations based on the nominal radiant outputs of the fire limit this jump distance to 60-70 feet except for the most unusual building configurations. Four factors, not presently evaluated, can contribute to this discrepancy. They are:

1) Interaction - At the present time, no enhancement (in terms of increased flame size and radiant output) is assumed when adjacent structures burn, and thus the net heating effect is considered to be the sum of that calculated for each structure burning individually. Interaction might be expected to increase the ordinary maximum jump distance by 20 or 30 feet, but would not in itself explain jumps of much larger distances.

2) Convection - At the present time, convective heating is not accounted for in assessing the susceptibility of exposed structures to ignition. Although convection can contribute to total heating over short distances (thus reducing the fire size required to make small jumps) it is not expected to greatly influence the rate of heating of structures near the maximum jump distances, except under conditions of very irregular terrain.

3) Radiant Peaking - Radiant exposures are generally considered to cause spontaneous ignitions when the flux level at the exposed surface reaches 0.8 cal/cm^2-sec. Pilot ignitions are considered to be possible at 0.3 to 0.4 cal/cm^2-sec. These levels were determined from experiments using constant heat flux exposures of various woods, which indicate that

approximately one minute of such exposure will cause ignition. Exposure to only slightly lower flux levels will produce no ignition even after an extended time period.

Assessment of the heat flux-time output of a burning building is usually accomplished by adding the radiant outputs from all window of actively burning rooms to some average contribution of flames above the roof. The exposure thus calculated is a fairly accurate measure of the average heating rate received by an exposed surface, but it does not account for the possible effects of short duration changes in the heating rate. There are times during a structural fire, however, when interior structural collapses produce momentary spurts of flame that may well ignite materials previously heated part way to their ignition temperature by the general fire level. This general level may then be adequate to sustain the ignition (in many cases heat flux levels of 0.1 cal/cm^2-sec are sufficient). This effect can be expected to influence the maximum jump distance expected, but will still not explain jump distances several orders larger than those presently calculated.

4) Fire Brands - Depending on their size and shape and on environmental conditions, such as the nature of the fire convection column and natural winds, firebrands can be carried for large distances (one mile is not uncommon in forest fires). This mechanism of fire spread certainly has the capability of explaining large jump distances. However, one cannot assume that all fires produce large numbers of brands which are carried great distances. At present, even reasonable estimates of firebrand sizes, shapes and frequency of generation in urban areas are not possible. Thus, careful study of this potential mechanism for fire spread over large gaps is indicated.

B. The Study of Fire Spread by Brands

The life of a firebrand can be generally subdivided into three intervals of interest, namely; generation, transport, and ignition of host materials. In statistical treatment of forest fire spread, these can be lumped together, that is to say, the overall effect of the three stages can be described in terms of fuel type, wind, humidity, etc. The fact that numerous forest fire records are available permits this approach. The results can be applied to certain urban or, at least, suburban areas that contain structures scattered throughout heavy vegetation. Southern California typically has such areas.

Apart from this one situation, peculiar to limited locations, adequate statistics are not available and an evaluation of urban fire spread by brands must presently treat each phase of firebrand life separately. Studies of each of these intervals can be conducted independently with no particular regard for sequential order. It can be anticipated, however, that results in each area may direct emphasis to certain portions of the other areas of study.

1. Firebrand Generation

During a fire, the contents and combustible structural elements of a building are gradually degraded, and the resulting loss of strength permits portions to separate through the actions of gravity, spalling and aerodynamic drag from fire induced or natural winds. Upon separation, some may settle in the debris and others may be carried aloft in the fire's convective column.

The period in which aerodynamic forces can be expected to be most effective is after penetration of barriers to vertical flow (roof and floor-ceiling constructions). At this stage of fire development, most types of building contents are fairly well consumed and the major producers of firebrands can be expected to be the combustible items of the building construction and, in particular, the various barriers to vertical flow. Apart from the study herein reported, no quantitative data exist and very little qualitative information is available beyond identification of wood shingles as producers of copious brands.

2. Firebrand Transport

A typical firebrand leaves its point of origin, rises within a convection column, leaves the column at some point and settles to earth. Its final location and size upon reaching this location depend on the relative magnitude of the horizontal and vertical forces which have acted upon it and the resultant time elapsed. Tarifa(3) has developed descriptions of relative motion between brands and the surrounding medium by measuring settling velocity for various brand sizes and shapes, and burning rates for various settling velocities. Away from the fire column, trajectories are readily defined by superimposing the prevailing wind upon the settling rate. Within fire columns, these descriptions may be difficult to apply.

The nature of the convective columns themselves are not well known. Studies have been conducted to describe the column associated with a firestorm(4,5,6) but nothing has been done for other mass fires or large area fires. The description of the trajectory of firebrands within a vertical column might be accomplished analytically by assuming the brand has a mean upward motion due to the column and a fluctuation, both horizontally and vertically, due to the column turbulence. The results of such a study will describe the fallout of brands at various elevations. A similar treatment of a non-vertical column will be needed but this best awaits development of an analytical model of the conflagration. It is anticipated that, for this development, it may be sufficient to add a steady, mean horizontal motion to the firestorm analysis. Certainly such an approach is a reasonable interim technique.

3. Ability of Firebrands to Ignite Host Materials

To properly evaluate the effect of firebrands, one must establish their ability to cause a significant fire once they land. This ability is a function of the material they contact and, in certain cases, the radiant energy received from the parent fire. Fire spread by brands into areas where blast has removed windows will certainly be more prevalent than into areas where windows are intact, due to the obvious susceptibility of interior combustibles to small brands. Some information presently exists concerning susceptibility of roofing materials(Ref.7) Additional information on the ability of brands to ignite both interior and exterior host materials is being generated as a part of OCD Work Unit 2539A.

III. THE EXPERIMENTAL PROGRAM

A. Fire Brand Generation Facility

A schematic diagram of the experimental facility constructed at IITRI's Fire Laboratory is shown in Fig. 1. The facility is composed of a reuseable fire chamber which is covered with the combustible roof segment being evaluated. The fire chamber extends through the Laboratory roof which contains a brand trapping screen and a quenching pool. The fire chamber is a vertical shaft eight feet square and twenty-two feet high. It is constructed of four foot by eight foot modules of expanded metal, framed with structural steel angles and coated with about 1-1/2 inches of furnace cement. The modules are supported by vertical pipes placed several inches outside the chamber thus formed (see Fig. 2). One module space is left open at the base of the chamber to provide combustion air. Two windows each 30 in.wide by 24 in.high are provided near the top of the chamber. One of these (downwind) was left open on each burn to provide exhaust for the combustion products prior to roof penetration. The fire was provided by four burners, one centered on each wall and five to six feet above the floor. Each burner directed flames horizontally toward the center of the chamber as well as toward the corners. Liquid propane was used as a fuel. Fuel delivery rates up to 3 gal/min were achieved by drawing the fuel as a liquid and passing it through a vaporizer prior to introduction in the burners.

Brands leaving the burning structure were trapped by a 1/2 inch mesh screen cage 25 ft square and 15 ft high. During each burn, two men with hoses were stationed on opposite sides of the cage to wash down any brands held against the screen by the wind or fire convective column. By directing the hose streams at an angle, this was accomplished without introducing water directly onto the fire. Most brands automatically fell

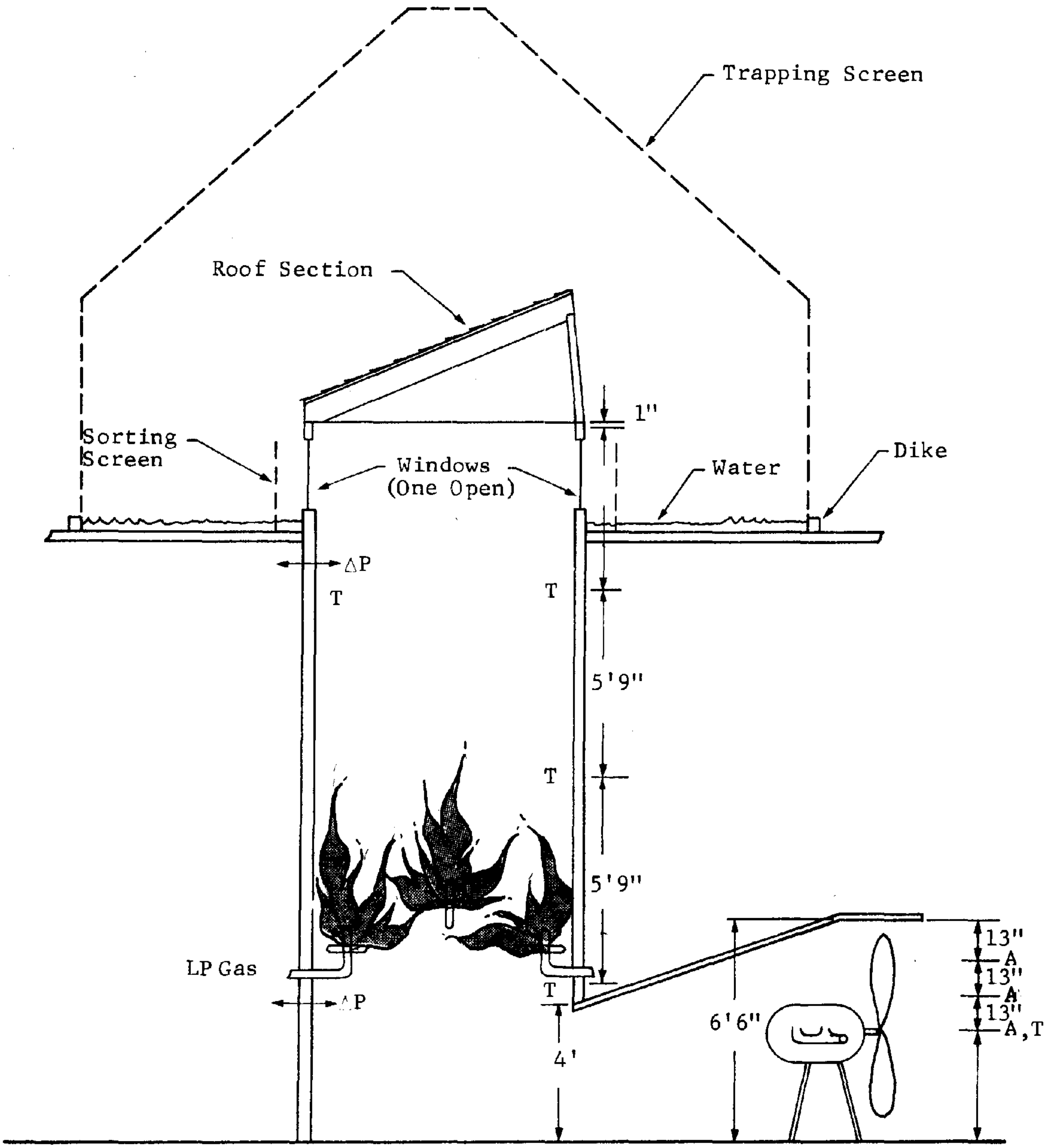


Fig. 1 SCHEMATIC OF FIRE BRAND GENERATION FACILITY (T: Thermocouple, A: Hot Wire Anemometer, ΔP: Differential Pressure Gauge)

Fig. 2 LOWER PORTION OF FIREBRAND GENERATION FACILITY DURING CONSTRUCTION

after striking the screen and were quenched in the water pool which covered the laboratory roof within the cage. The sorting screen shown in Fig. 1 was used to separate burning members which dropped from the roof from the true flying brands. A photograph of the upper portion of the test structure is shown as Fig. 3. In order to superimpose additional pressures representative of larger fires or wind impingement on window openings, an aircraft engine was placed in a shroud which was attached to the 4 ft x 8 ft opening at the bottom of the fire chamber.

Instrumentation locations are also shown in Fig. 1. Temperatures were measured at several heights in the fire chamber including locations immediately under the roof section. An entering air temperature was measured upstream from the engine. Pressure differences between the fire chamber and the main laboratory were monitored at heights of 4 ft and 17 ft above the floor. Three hot wire anemometers were placed at the inlet to the shroud to measure entering air flow. In addition, a pitot tube was placed near the middle anemometer for indication of the higher flow rates.

B. Roof Constructions Evaluated

The particular roof structures studied were selected to include representation of the more common construction in combinations that allowed for variation of significant parameters. A complete listing appears in Section IV-A. The parameters were chosen as follows (note - all combinations of parameters were not tested):

1. Sheathing

Three thicknesses of sheathing were used: 2 in. and 1 in. lumber, and 5/16 in. plywood. These were chosen as most common while sufficiently different to provide indication of the importance of sheathing thickness in overcoming the effects of covering. As older homes in particular contain wood shingles applied over open spaced sheathing, this combination was included. With the exception

Fig. 3 FIRE RESEARCH LABORATORY ROOF SHOWING UPPER PORTION OF BURNOUT STRUCTURE, FIRE BRAND TRAP AND QUENCHING POOL

of the 5/16 in. plywood, all sheathing and framing lumber was purchased from a local salvage yard and was well aged. The two inch lumber was fir and the one in. lumber was yellow pine.

2. Covering

Covering materials included:

a) Two weights of asphalt shingles.

b) Roll roofing to indicate the effect of continuous covering.

c) Built up roofing (one layer of 15 lb. roofing paper cemented to sheathing, one layer of 90 lb. roll roofing cemented to paper, all seams lapped and nailed) to show the behavior of continuous covering in tight contact.

d) Cement-asbestos shingles which might affect brand production during spalling.

e) Wood shingles. These roof sections were weathered through one winter and summer prior to test.

Roofs with no covering were also included to serve as a base for comparisons as well as to provide some indication of the behavior of simple floor construction.

3. Pitch and Configuration

Three roof pitches were selected for study: flat, medium (5 in. rise per foot), and high (12 in. rise per foot). In addition, a hip roof was included since many short rafters occur in such construction.

It should be noted at this point that a common problem in studying the behavior of construction segments is the tendency for segments to be structurally stronger than full size components. To maintain a reasonable match to longer spans in terms of strength, the high, hip, medium and low pitch roofs used nominal 2 x 4, 2 x 4, 2 x 5 and 2 x 6 rafters respectively. In addition, approximately 50 percent of the sheathing boards were purposely made up of two or more butted pieces.

4. Internal Pressures

Although not a construction parameter, it seems appropriate to mention induced pressures at this point. Fire chamber pressures without induced wind were typically zero at the 5 ft. height and 0.08 to 0.10 in. H_2O at the 17 ft. height. Calculation will show that for fire temperatures of 1600°F, pressure differences of 0.11 in. H_2O for every 10 ft. of column height could occur. This is not quite achieved since the open window relieves the pressure to some extent. In larger structures with undivided interior spaces, one can expect to closely approach the figure of about 0.11 in. H_2O for each 10 ft of height, at least until the roof barrier is significantly breached. In structures with numerous interior partitions, this will not be the case and values much like those from the chamber should occur.

Internal pressures can also be generated through the action of wind impinging on the side of the structure. Where the interior of the structure has partitioning, the portion near the upwind side may be pressurized to levels closely resembling the stagnation pressure of the wind. Typical stagnation pressures are listed below:

TABLE I - WIND PRESSURES

Wind Velocity (mph)	Stagnation Pressure in. H_2O
10	0.05
20	0.19
25	0.30
30	0.44
40	0.77
60	1.74

For the above reasons, data were collected for several roofs at 0.3 to 0.5 in. H_2O induced pressure and for one roof construction at several pressure levels up to about 0.6 in. H_2O.

The various roof sections were placed atop the fire chamber but not attached by nails or bolts. Gable ends were closed with sheet metal, nailed in place. Fig. 4 shows sketches

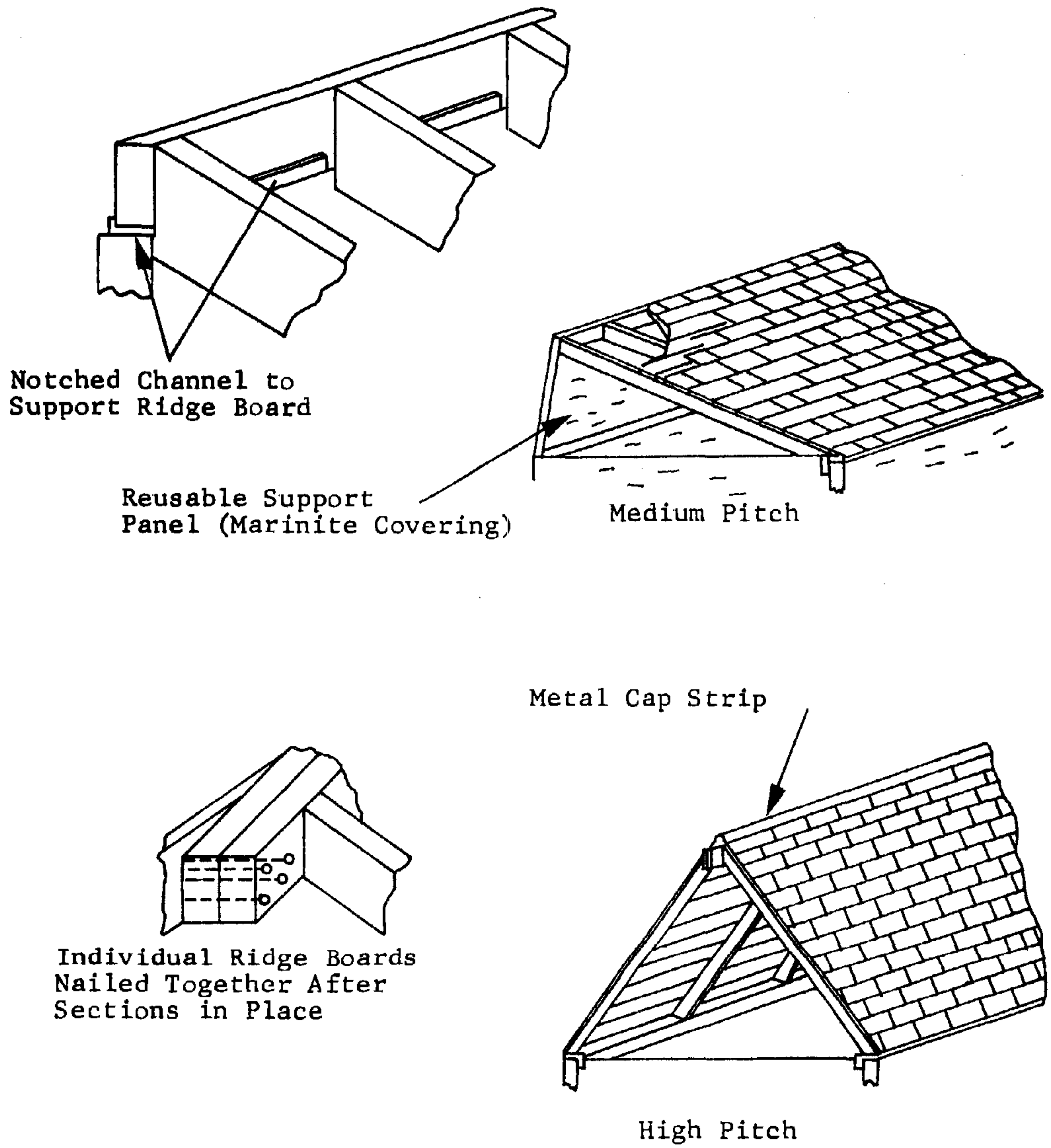


Fig. 4 INSTALLATION OF MEDIUM AND HIGH PITCH ROOFS
(END CLOSURES OF SHEET METAL NOT SHOWN)

of the medium and high pitch roof sections and indicates their mode of support. Rails were attached to the high pitch roofs to prevent end rafters from falling beyond the sorting screen during collapse.

C. Experimental Procedure

Prior to each test, the roof section was installed, the quenching pool covered with sorting screens (described later) and filled, and cooling water flow started through the pipes supporting the brand trapping screen. To start the test, the burners were adjusted to raise the temperature of the top of the fire chamber to 1500 to 1600°F in 2 to 3 minutes and hold it there. Simultaneously, the aircraft engine was started if needed and its speed adjusted to produce the desired initial wind pressure. Once adjusted, the engine speed was normally held constant throughout the test. As roof penetration took place additional gas was introduced into the chamber to maintain the upper chamber temperature at 1600°F until about 25 percent of the roof was open. This gas flow was then maintained throughout the remainder of the test. This was done to simulate the burning rate of combustible building structure and contents which increases when additional air becomes available until limited by fuel surface area. Obviously, many combinations of fuel surface and arrangement could produce varied burning rate-time relations. The simulation chosen had the advantage of being readily repeatable.

Throughout each burn, visual and photographic observations were made from the laboratory roof. Flame locations, penetrations and collapse times were noted. At the same time, falling embers that occasionally dropped beyond the sorting screen were noted for subsequent removal. During the period of brand production, water sprays were directed on the brand trapping screen as needed to extinguish and drop any brands that did not automatically fall to the quenching pool.

After the first few burns it became very apparent that little raw wood remained in the brands. Upon hitting the quenching pool, they invariably sank to the bottom thus eliminating skimming techniques from being used for their collection. As a result, the system of sorting screens was devised and used for the remaining experiments. These consisted of stacks of three screens,one inch hexagonal mesh, one half inch square mesh (7/16 inch openings) and seven mesh (1/8 inch openings). Each stack was approximately six feet wide and ten feet long. Upon completion of a burn, they were carefully lifted from the pool thus sorting the collected brands into three size categories. Each screen with brands was photographed and the brands then washed onto a collecting table and eventually into a storage basket. As the large brands were quite fragile when wet (due to their high weight in this condition), they were collected by hand from the coarse screen and counted during collection. This technique was impractical for most medium and fine mesh screens and they were merely collected into the storage baskets for later evaluation.

The storage baskets of brands were placed in a drying room for a minimum of one week and then treated in the following manner. Each basket was weighed and a sampling of brands removed. This sampling was counted and also weighed. The sampling was then oven dried and reweighed. From this information, the oven dry basket weight and the total brands in each basket (except those already counted for the coarse screen) were calculated.

IV. RESULTS AND CONCLUSIONS

A. General

Table II gives a general listing of all the experiments. The data have been arranged so that experiments with similar roof constructions are grouped together. Thus, the listing starts with all roofs having no covering, then follows with those covered with 235# asphalt shingles. The next group includes the remaining coverings over 1 in. sheathing and is followed by a miscellaneous category. The remainder of the table lists results with wind induced pressures (the previous listings are all for no wind) in the same general order, where possible, as those for no wind.

Included in Table II are the roof and wind descriptors as well as the time histories of several stages of each fire. For this listing, penetration was taken to mean the presence of a visible hole rather than the 1st appearance of flame since some penetrations of cracks came earlier but did not indicate a start of brand production. A major opening was first defined to be about 25 percent of the roof area. The time at which this occurred was later noted to be approximately the time at which static pressure beneath the roof dropped to ambient and this latter time was used in the table. Additional columns in Table II give the weights and numbers of brands collected on each screen as well as totals. Where unusually large brands were noted these are listed in a separate column in addition to being included in the numbers from the coarse screen. As mentioned earlier, the screens were seven mesh (fine) two mesh (medium) and one mesh (coarse). The final columns of Table II show the average brand weights calculated for each screen along with an overall average for the burn.

Table II

SUMMARY OF EXPERIMENTAL RESULTS

Burn No.	Pitch	Roof Area (ft^2)	Sheathing (in)	Covering	Wind Pressure ("H_2O)	Total Pressure ("H_2O)	Ambient Wind (MPH)	Ign. to First Penetration (Min)	Ign. to Major Opening (Min)	Major Opening to End of Test (Min)	1st Penetration to End of Test (Min)	Total Test Time (Min)	Weight of Brands (Grams): Fine	Medium	Coarse	Total	Number of Brands: Fine	Medium	Coarse	Total	No. of Brands > 9 in^2	Average Brand Weight (Grams): Fine	Medium	Coarse	Total
1	Med.	64	2	0	0	.14	NE 4-8	10	15½	3½	9	19	118	91	14	227	5,436	413	14	5,863	0	0.02	0.23	1.0	0.04
12	Med.	64	5/16 Ply	0	0	.15	SE 4-7	2½	4	12	13½	16	45	73	106	224	1,711	773	88	2,572	3	.03	.094	1.21	.09
32	High	91	1	0	0	.14	SSW 12-15, 20 Gusts	4	8	5½	9½	13½	320	867	1,330	2,517	6,769	4,073	292	11,134	19	.05	.21	4.55	.23
5	Med.	64	1	0	0	.15	NE 6-8	4	7½	8½	12	16	245	519	731	1,495	5,263	2,057	*500	7,820	9	.05	.25	1.46	.19
21	Med.	64	1 Rafters	0	0	.14	---	5¼	6¾	1½	3	8½	17	10	0	27	518	64	0	582	0	.03	.16	--	.05
42	Low	64	1	0	0	.13	SW 6-8	5¼	6½	7½	8¾	14	117	208	163	488	1,940	717	76	2,733	1	.06	.29	2.15	.18
34	High	91	1	235#	0	.14	W 5-8	13	15	1	3	16	79	254	387	720	1,524	789	134	2,447	2	.05	.32	2.89	.29
28	Hip	69	1	235#	0	.14	SE 0-2	15	17	0	2	17	18	9	9	36	851	43	5	899	0	.02	.21	1.84	.04
6	Med.	64	1	235#	0	.17	SW 6-8	11½	15½	3¾	7¾	19½	128	230	540	898	3,868	488	*300	4,656	1	.03	.47	1.80	.19
7	Med.	64	1	235#	0	.15	N 6-8	10½	13¾	1½	4¾	15½	48	112	155	315	1,495	247	60	1,802	1	.03	.46	2.59	.17
30	High	91	5/16 Ply	235#	0	.14	SW 4-5	8	10	6	8	16	185	627	462	1,274	8,306	3,124	578	12,008	0	.02	.20	.80	.11
18	Med.	64	5/16 Ply	235#	0	.14	SE 12-16	9	11	5½	7½	16½	43	190	77	310	2,582	1,603	97	4,282	0	.02	.12	.79	.07
17	Med.	64	2	235#	0	.15	SE 12-20	13½	17	5¾	9½	22¾	0	0	0	0	0	0	0	0	0	--	--	--	--
9	Med.	64	1	A.C.	0	.15	NNE 6-8	6½	11¾	3	8½	14¾	52	151	290	493	1,007	460	42	1,508	3	.05	.33	6.89	.33
33	High	91	1	300#	0	.14	W 8-12, 20 Gusts	12½	15½	1	4	16½	265	535	520	1,320	10,044	2,188	226	12,458	2	.03	.24	2.30	.11
8	Med.	64	1	300#	0	.15	SW 3-4	16	17¾	1½	3	19	50	77	79	206	2,104	109	30	2,243	0	.02	.71	2.61	.09
11	Med.	64	1 Open	Wood	0	.15	NE 4-9	4	7½	4	7½	11½	262	759	1,665	2,687	16,828	11,271	2,271	30,370	Many	.02	.067	.73	.09
13	Med.	64	1	Wood	0	.14	NW 6-12	4	11	¾	7¾	11¾	199	666	1,212	2,077	13,773	8,223	1,130	23,126	Many	.01	.081	1.07	.09
16	Med.	61	1 Open	Wood RE Roof 300#	0	.15	SW 10-14, 18 Gusts	10½	14¾	3½	7¾	18½	116	208	308	692	4,662	1,566	420	6,648	--	.02	.13	.73	.095
23	Med.	64	1	Roll	0	.15	SSW 8	5¾	6¾	9½	10½	16	19	4	0	23	607	49	0	656	0	.03	.09	--	.035
40	Low	64	1	Roll	0	.13	SW 8-10	13½	17½	½	4½	17¾	40	47	64	151	1,818	220	24	2,062	0	.02	.21	2.66	.07
39	Low	64	1	Builtup	0	.13	SW 7-8	14¼	20¼	½	6½	20¾	0	0	0	0	0	0	0	0	0	--	--	--	--
41	Low	64	5/16 Ply	Roll	0	.15	W 8-12, 25 Gusts	5¼	8½	****8	11½	16½	116	112	94	322	2,215	449	81	2,745	0	.05	.25	1.16	.12
24	Med.	64	5/16 Ply	Roll	0	.14	SSW 6-8	4½	7	7	9½	14	59	183	116	358	2,793	1,339	104	4,236	0	.02	.14	1.11	.08
26	Med.	64	5/16 Ply	300#	0	.15	SW 3-5	9½	11	5	6½	16	51	122	28	201	2,046	893	32	2,971	0	.02	.14	.88	.07
35	High	91	1	235#	.22	.31	SSE 5-7	6½	9½	2	5	11½	324	838	1,304	2,466	12,798	5,403	410	18,611	14	.03	.16	3.18	.13
36	High	91	1	235#	.43	.49	S 7-9	5	8	2	5	10	419	864	1,638	2,921	16,219	10,976	274	27,469	29	.03	.08	5.98	.11
37	High	91	1	235#	.55	.63	SW 18-20	4½	7½	1½	4½	8¾	615	1,298	2,975	4,888	31,312	11,430	504	43,246	49	.02	.11	5.90	.11
29	Hip	69	1	235#	.47	.52	NNE 8-12	7	9½	0	2½	9½	59	60	102	221	1,886	343	43	2,272	3	.03	.17	2.37	.10
14	Med.	64	1	235#	.48	.57	S 8-14, 26 Gusts	3¼	8¾	1½	7	10¼	741	1,398	1,298	3,437	17,072	5,135	440	22,647	19	.04	.27	2.95	.15
27	Med.	64	1	235#	**.75 OSC	**.83	W 8-12, 16 Gusts	4	7¼	2¾	6	10	385	712	1,212	2,309	13,092	3,642	260	16,994	3	.03	.20	4.66	.14
19	Med.	64	5/16 Ply	235#	.39	.50	SE 7	4	7	7	10	14	197	347	304	848	4,846	1,730	250	6,826	1	.04	.20	1.22	.12
20	Med.	64	2	235#	.44	.53	SE 8	11¾	12¾	1½	2½	14½	81	59	23	163	3,727	340	47	4,114	0	.02	.17	.49	.04
25	Med.	64	1	A.C.	.44	.58	WSW 6-8	5	8	3	6	11	274	1,195	1,402	2,871	6,704	7,313	455	14,472	--	.04	.16	3.08	.20
10	Med.	64	1	300#	.30	.38	WSW 6-8	5	8	3½	6½	11½	257	1,196	1,037	2,490	6,878	4,656	428	11,962	11	.04	.26	2.42	.21
31	High	91	1 Open	Wood	.41	.50	WSW 5-6	3	4½	***6½	8	11	736	2,087	4,124	6,947	44,369	29,602	1,396	75,367	Many	.02	.07	2.95	.09
15	Med.	64	1 Open	Wood	.50	.59	NW 8-12, 16 Gusts	3¼	4½	2¾	4	7¼	224	769	2,733	3,726	9,593	8,848	1,078	19,518	Many	.02	.087	2.54	.19
22	Med.	64	1	Roll	.45	.54	SSW 5-8	3½	5	1½	3	6½	117	75	12	204	4,457	308	7	4,772	0	.03	.24	1.77	.04
38	Low	64	1	Builtup	.42	.48	SSE 8-10	5½	9½	4½	8½	14	433	1,038	1,081	2,552	16,842	5,073	292	22,207	10	.03	.20	3.70	.11

* ESTIMATES, SAMPLING TECHNIQUE FOUND TO BE INADEQUATE (NUMBERS MAY BE HIGH)

** MAXIMUM VALUE OF OSCILLATING PRESSURE (CYCLED ABOUT 4-5 TIMES/MIN)

*** BARE RAFTERS DURING LAST FIVE MINUTES OF THIS PERIOD

**** BARE RAFTERS DURING MOST OF THIS PERIOD

Tables III, IV, and V are bar graphs to provide rapid comparisons between burns. Table III includes the roofs with no cover and those covered with 235# asphalt shingles (no wind). Table IV contains all other experiments without wind. Table V includes all experiments with wind. The first column of bar graphs on each table represents the weight distributions of brands collected by the three sorting screens. Weight rather than number was chosen since the relative weights on each screen were of similar magnitudes which lends ease to visual comparisons. The summation of the three bars from a burn is approximately proportional to the brands per unit plan area as each roof covered about the same floor area.

The second column of bar charts describes the total weight and numbers of brands per unit area of roof surface. The weight units of grams/ft^2 were retained as they yielded small integers with which to describe the results. In order to examine the possibility that differences in total brands produced could be attributed to different time intervals being available for production, a rate of production was displayed as the last column of bar charts. The time used to calculate these rates was the time from roof penetration to collapse. This "average" rate does serve as an indicator although one should not assume a uniform rate of brand production throughout this period. The fallacy of such an assumption was visibly evident in several burns involving plywood or wood shingles where periods of almost no brand production occurred after the sheathing was consumed but the rafters had not collapsed. In two burns, this time was a significant portion of the total and is so noted in Table II.

B. Effects of Construction

This section treats those results obtained under conditions where no superimposed wind pressure is added to that generated by the moderate, two story fire. Under these conditions, the outstanding brand producer was the wood shingle roof.

TABLE III BRANDS PRODUCED BY ROOFS WITH NO COVERING OR WITH 235# ASPHALT SHINGLES

RUN NUMBER	COVERING	SHEATHING	PITCH	WIND PRESSURE ("H_2O)	COLLECTED BRAND WEIGHTS* (GRAMS) 0 500 1000 1500 2000 2500	BRANDS/FT^2 WT 0 10 20 30 40 50; NO 0 50 100 150 200 250	BRANDS/FT^2-MIN WT 0 2 4 6 8 10 12; NO 0 10 20 30 40 50 60
4	0	2"	MED	0	F M C	WT NO	WT NO
12	0	5/16" PLY	MED	0	F M C	WT NO	WT NO
32	0	1"	HIGH	0	F M C	WT NO	WT NO
5	0	1"	MED	0	F M C	WT NO	WT NO
21	0	1" (RAFT)	MED	0	F M C O	WT NO	WT NO
42	0	1"	LOW	0	F M C	WT NO	WT NO
34	235#	1"	HIGH	0	F M C	WT NO	WT NO
28	235#	1"	HIP	0	F M C	WT NO	WT NO
6	235#	1"	MED	0	F M C	WT NO	WT NO
7	235#	1"	MED	0	F M C	WT NO	WT NO
30	235#	5/16" PLY	HIGH	0	F M C	WT NO	WT NO
18	235#	5/16" PLY	MED	0	F M C	WT NO	WT NO
17	235#	2"	MED	0	F O M O C O	WT O NO O	WT O NO O

*F: 7 MESH SCREEN
M: 2 MESH SCREEN
C: 1 MESH SCREEN

TABLE IV BRANDS PRODUCED BY MISCELLANEOUS ROOFS (NO WIND)

BURN NUMBER	COVERING	SHEATHING	PITCH	WIND PRESSURE ("H_2O)
9	A.C.	1"	MED	0
33	300#	1"	HIGH	0
8	300#	1"	MED	0
11	WOOD	1" OPEN	MED	0
19	WOOD	1"	MED	0
16	WOOD REROOF 300#	1" OPEN	MED	0
23	ROLL	1"	MED	0
40	ROLL	1"	LOW	0
39	BUILT UP	1"	LOW	0
41	ROLL	5/16" PLY	LOW	0
24	ROLL	5/16" PLY	MED	0
26	300#	5/16" PLY	MED	0

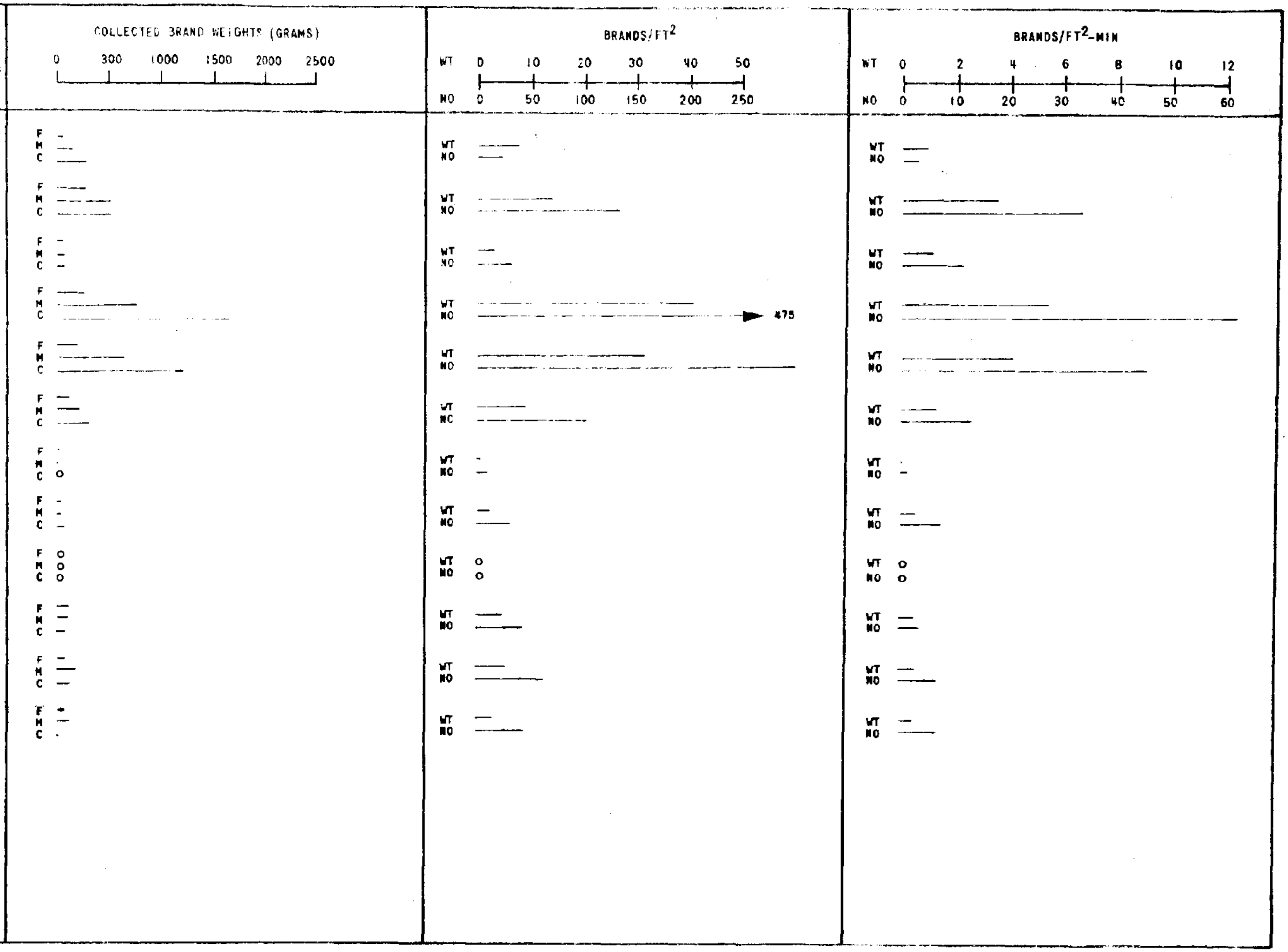
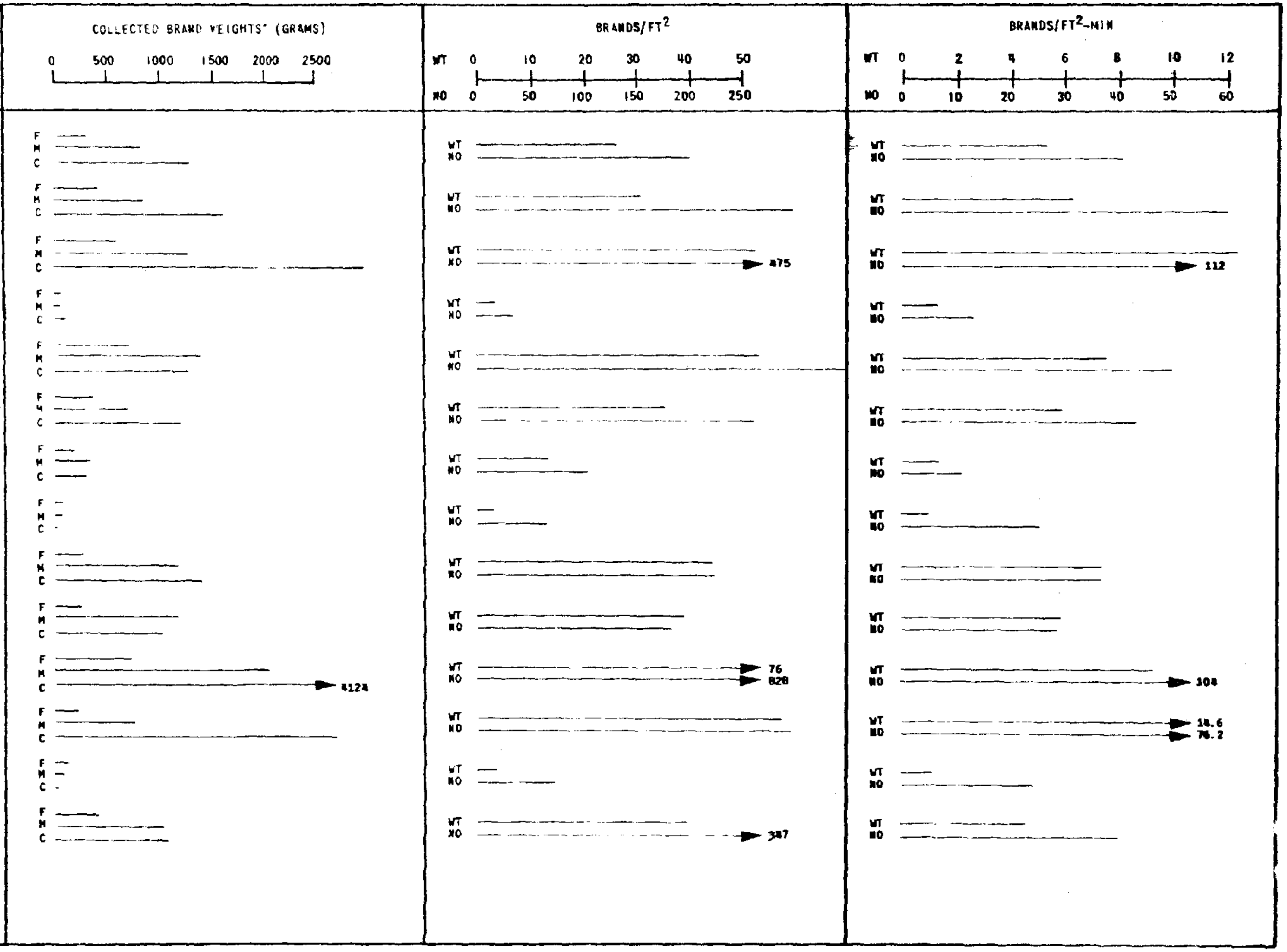


TABLE V EFFECT OF WIND PRESSURE ON BRAND PRODUCTION

BURN NUMBER	COVERING	SHEATHING	PITCH	WIND PRESSURE ("H_2O)
35	235#	1"	HIGH	.22
36	235#	1"	HIGH	.43
37	235#	1"	HIGH	.55
29	235#	1"	HIP	.47
14	235#	1"	MED.	.48
27	235#	1"	MED.	.75OSC
19	235#	5/16" PLY	MED.	.39
20	235#	2"	MED.	.44
25	A.C.	1"	MED.	.44
10	300#	1"	MED.	.30
31	WOOD	1" OPEN	HIGH	.44
15	WOOD	1" OPEN	MED.	.50
22	ROLL	1"	MED.	.45
38	BUILT UP	1"	LOW	.42



Not only did the wood shingles become brands, but they provided little or no inhibition to production of brands by the one inch sheathing to which they were attached.

Examination of Tables III and IV shows that total brand production and rate of production from wood shingle roofs, are both far greater than from any other covering-sheathing combination. They also greatly exceed the brand production rates and quantities from those burns where no covering was present. Other roofs tended to be moderate in brand production and in many cases the differences between burns with different roofs are within the variations noted for repeat burns of the same configuration. The variation can be attributed to some degree to variations in the development of openings and the stages of collapse as the structure weakens. Changes in wind (or large volume fire) induced pressures quickly overshadow many of these small variations. For this reason, the many burns that would be necessary to allow statistical treatment of each configuration for fine gradation of all contributing construction factors is unwarranted.

Examination of Table III does show that bare one inch sheathing produced more brands than did either the 5/16 in. plywood or the 2 in. lumber. The 2 in. lumber came close to producing the same total number of brands but the brands were much smaller. The small brands are produced mainly by spalling action which was most prevalent in the 2 in. lumber, and is caused by entrapment of moisture and gases within the wood. Should the smaller brands prove to be insignificant in terms of eventual fires started, the difference in hazard presented by the different sheathings would be accentuated.

Roof pitch for bare sheathing cases (Table III) seemed to have a slight effect on brand production rate and quantity in that the flat roof produced measureably less brands than did the medium or high pitch roofs. This can be attributed to less chance for ambient wind to directly affect the sheathing on the flat roof. Also the sheathing becomes more resistant to gravitational forces as pitch is raised and thus has less tendency to break and fall before becoming light enough to fly.

Experiment 21 (Table III) was included to determine if reducing the supporting strength of the rafters would result in greater production of brands. The reverse occurred since that period when the rafters are supporting partially burned sheathing is a period of high rate of brand production.

Addition of 235# asphalt shingles to the one inch sheathing reduced brand production (Table III). This was apparently accomplished by extending the time to penetration and thus reducing the period of brand generation. The comparisons in Table III show that the total brands produced decreased when the 235# shingles were applied while the rate of production showed little effect. The average brand weight showed no marked change.

Any reduction in brands derived from increasing the asphalt shingle weight to 300# on 1 in. sheathing was minor. Burn number 33 (Table IV), in fact shows an increase in production. However, this can be attributed to rather high, gusty ambient winds which, although blocked from affecting the internal pressure, did act on this high pitch roof from the side.

The addition of extra shingles did show a marked effect in the case of the hip roof. This experiment was included to determine if the many short rafter and sheathing sections found near the peaks in such roofs would increase brand production. Any such potential was not realized since the additional shingles used to cap the hip rafter joints, coupled with the added strength near the peak due to the short lengths of sheathing, produced a roof that remained quite free of penetrations until the perimeter became quite weakened. At this point, total collapse occurred which consisted of almost the entire roof as a single unit. This equivalent portion of a larger roof can be expected to behave in much the same way.

None of the coverings showed a significant ability to reduce the rather low brand production of the 5/16 in. plywood roofs. Total brand weights were about the same while a slight increase appeared in the number of brands produced (for example, Burns 12 and 18 - Table III). This is probably caused by the tendency of the covering to restrict the opening, so that the upward gas velocity and thus the rate of brand production increased although brand size decreased. The covering reduces the time elapsed from penetration to collapse and this approximately counter-balances the increased weight rate of brand production.

Burn 16 (Table IV) indicates that an added covering can do much to counteract the effects of wood shingles. Burn 17 (Table III) appears to support a contention that, under low induced pressures, covering material can contain 2 in. sheathing through the significant spalling period (very few small brands were noted coming through the window prior to roof penetration where they impinged on the sorting screen and fell to the inner pool area).

The continuity of coverage afforded by roll roofing (it was noted on several occassions to balloon slightly while still retaining continuity prior to penetration) appears to prevent a part of the period of high brand production rate of 1 in. sheathing (note - both low total brands and low rates of production for Burns 23 and 40 - Table IV). The additional benefit of cementing the covering layers to each other and to the sheathing is shown by Burn 39 (Table IV) in which the roof layers were identical to those of Burn 40 except for the cement. Shingled roofs, particularly the spot cemented type, that have sustained several hot summers may behave, at least to a degree, like roofs with continuous cemented covering.

C. Effects of Wind Pressure

Table V gives immediate and obvious evidence that brand production is extremely sensitive to internal pressure (superimposed wind or large fire size). To facilitate comparisons of Tables III and IV with Table V, a brief summary is presented in Table VI, below.

TABLE VI EFFECT OF WIND ON BRAND PRODUCTION

Burns	Cover	Pitch	Sheathing	Wind Pressure ("H_2O)	Wind:No Wind Ratio	
					Wgt.	Number
22-23	Roll	Med	1"	.45	8.9	7.3
9-25	A. C.	Med	1"	.44	5.8	9.6
8-10	300#	Med	1"	.30	12.1	5.4
11-15	Wood	Med	1"open	.50	1.39	0.64
18-19	235#	Med	5/16" Ply	.39	2.74	1.59
7-14	235#	Med	1"	.48	10.9	12.6
34-35	235#	High	1"	.22	3.4	7.6
34-36	235#	High	1"	.43	4.1	11.2
34-37	235#	High	1"	.55	6.8	17.6

In addition, two roofs that did not produce brands without wind, do so with wind (built-up and 235# on 2" sheathing). One can surmise that the lack of a major increase in brand production by the wood shingled roofs is due to the fact that the shingles were such highly efficient brand producers under no wind conditions. The moderate increase for 5/16" plywood sheathing is probably due to the limited availability of material for brand production. (The plywood is fairly well exhausted before the covering is penetrated since the many gaps present between sheathing boards do not exist in the plywood.) Comparison of the appropriate parts of Table V with III and IV shows that both total brand production and rate are increased to about the same degree by the wind while the period of brand production does not materially change.

In the previous section on construction features, it was noted that the built-up roof seemed to inhibit brand production to some degree due to the cementing of covering to sheathing. At the 0.4 in. H_2O wind pressure level, the reverse seems to be occurring (Burns 22 and 38). Here, the covering was being blown by the internal chamber pressure and, in the process, helping to tear wood brands loose.

Burn 20 with 2" sheathing and 0.44 in. H_2O wind induced pressure produced only a small number of brands. The larger of these, however, were somewhat smaller in size than those produced in full scale burns of buildings with similar roof construction (Ref. 8). This can probaly be attributed to the use of 12" wide sheathing boards in the laboratory tests while the real structures were sheathed in 6" wide lumber. In addition, the active fire heights ranged from 35 to 75 feet at the time of roof penetration in the real structures, which in turn had moderate superimposed winds.

The most complete set of wind data was obtained on high pitch roofs with 235# asphalt shingles and 1 in. sheathing. These results are shown in Fig. 5 as total weight, total number, and number of large brands produced by various wind induced pressures. For other data, refer to Tables V and VI.

Figure 6 shows that the average weight of brands collected on the 2 and 7 mesh screens decreases as wind is increased while that for brands collected by the 1 mesh screen increased. Apparently in the presence of wind, the finer screens collect particles that are less spherical in shape, which reduces the ratio of weight to maximum dimension.

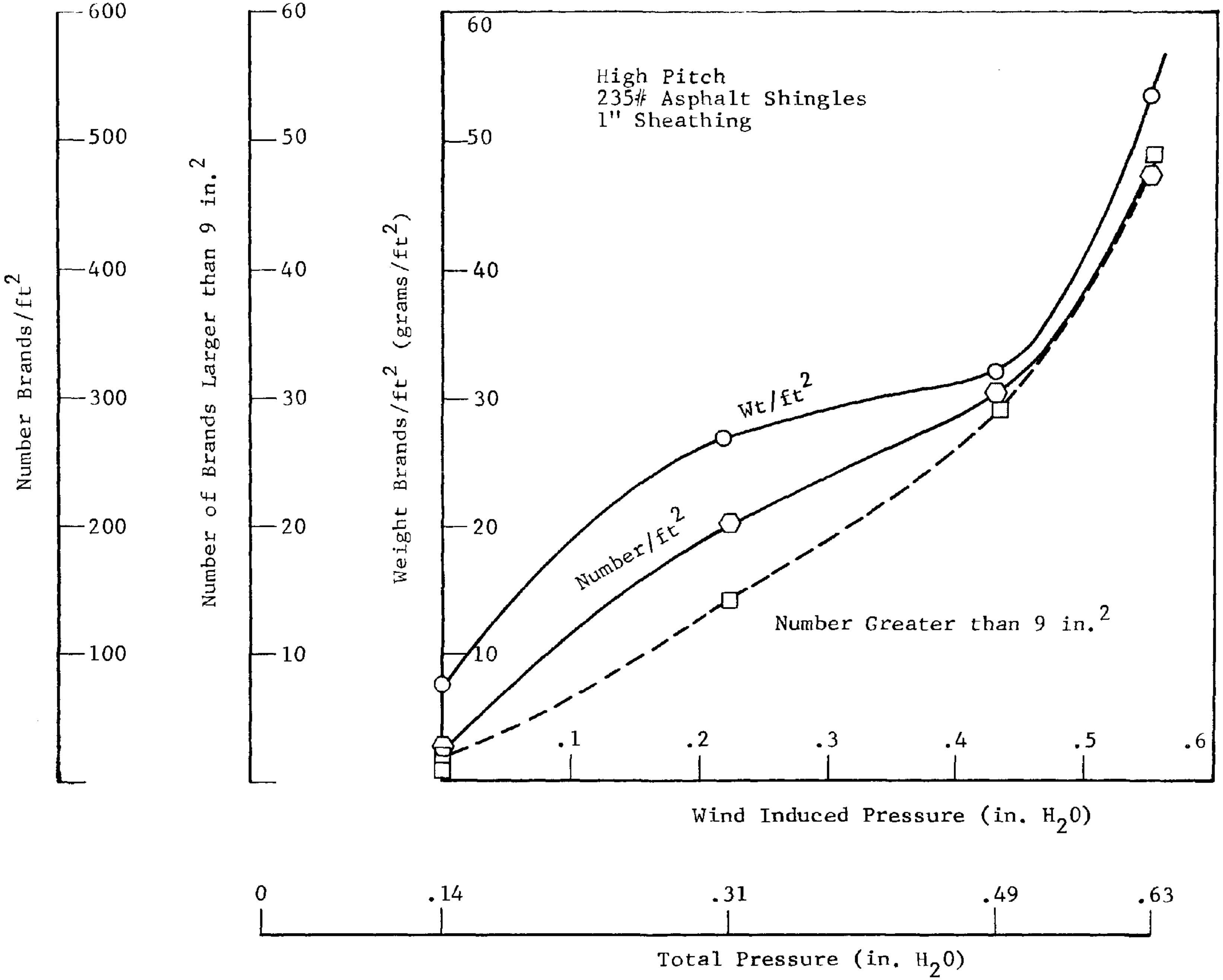


Fig. 5 EFFECT OF INTERNAL PRESSURE ON FIREBRAND PRODUCTION

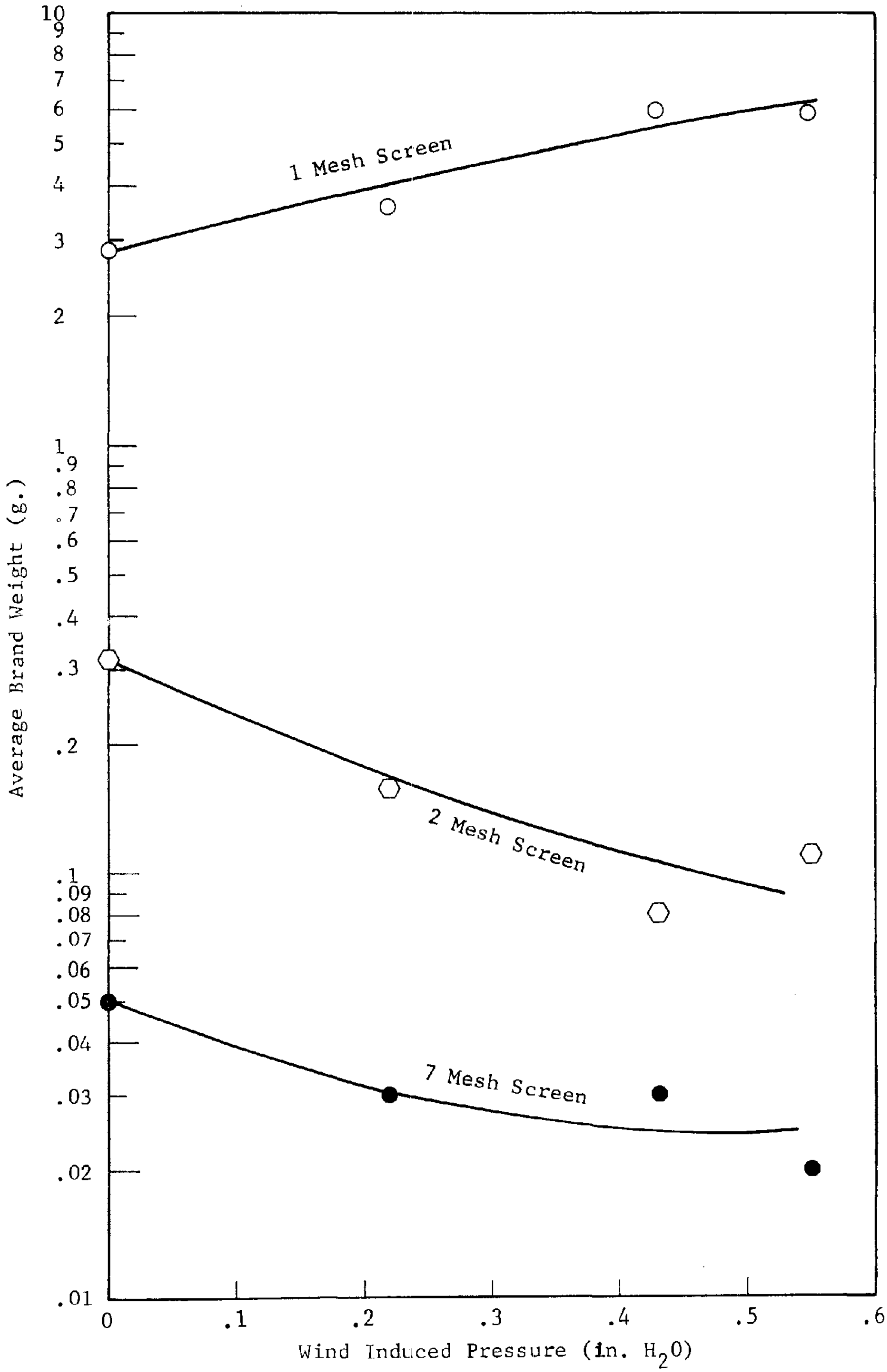


Fig. 6 EFFECT OF WIND PRESSURE ON FIREBRAND WEIGHT/SIZE RATIO (High Pitch, 235# Asphalt Shingles, 1" Sheathing)

The coarse screen collects all brands larger than one inch and thus the total weight collected is not sensitive to shape. The brands collected on this screen were generally larger with wind than without.

Figure 7 shows data for several other roof segments with and without wind. The results with AC shingles on 1" sheathing showed that wind produced minor decreases in average brand weights on all three screens. The reason for this on the coarse screen is unknown but may be due to the brands being broken up by the spalling action of the AC shingles. The roof containing plywood sheathing and the one with wood shingles over open 1" sheathing both give increased brand size with increased wind for all screens. On the coarse screen it is expected. For the other screens with wood shingles it probably is due to the brands being burned more thoroughly without wind and thus being lower in weight per unit area. The same can hold true for the plywood with the added possibility of ply separation forming thinner brands. The brands as collected can be characterized as being slightly arched but fairly smooth when their source was plywood or wood shingles. The smaller brands from 1" sheathing were almost spherical in shape. The larger ones were checkered in about a 3/4" grid by cracks and fissures which apparently would burn through eventually producing almost spherical segments (see Fig. 8). For additional average brand weights, see Table II.

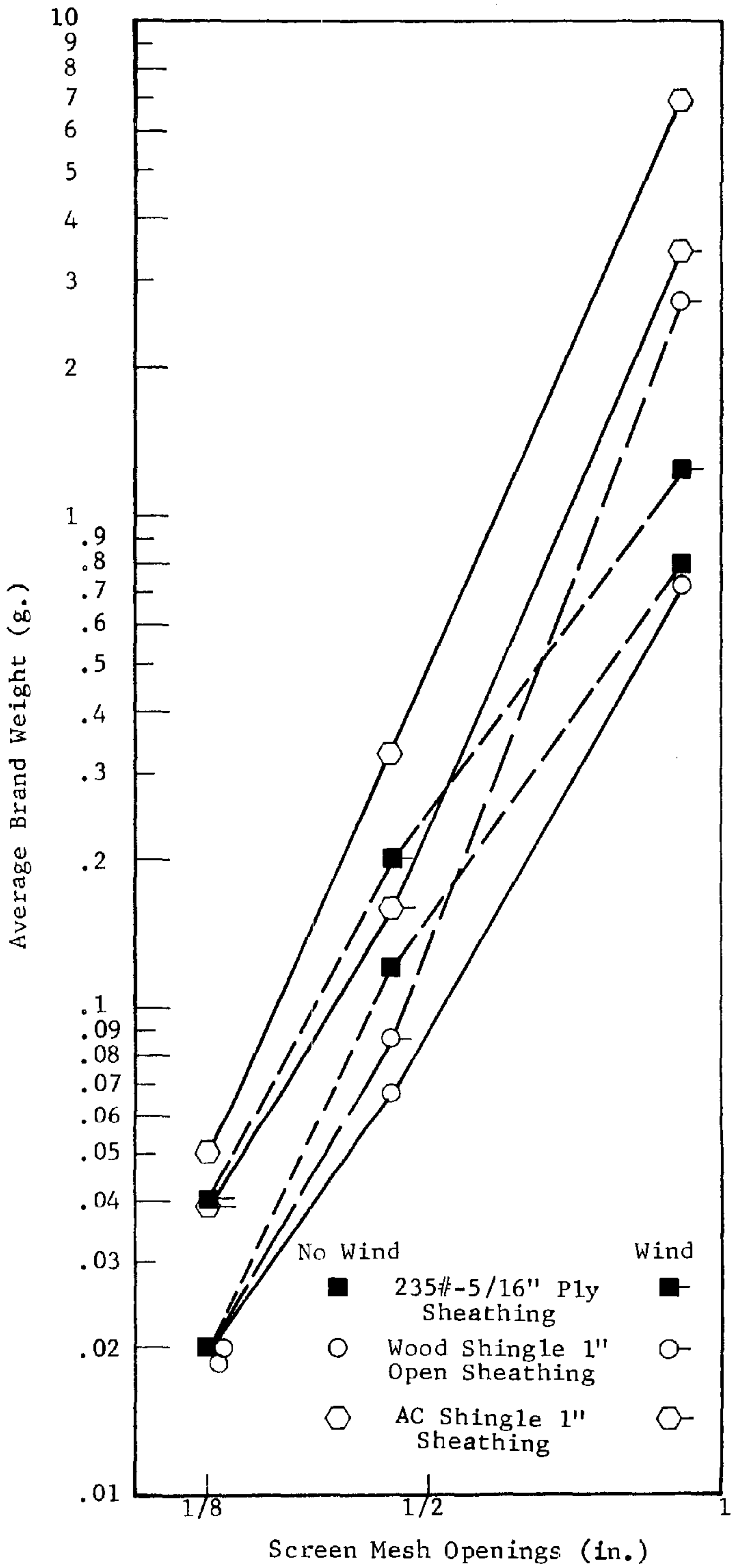


Fig. 7 AVERAGE BRAND WEIGHTS COLLECTED ON SORTING SCREENS FOR VARIOUS ROOF CONSTRUCTIONS

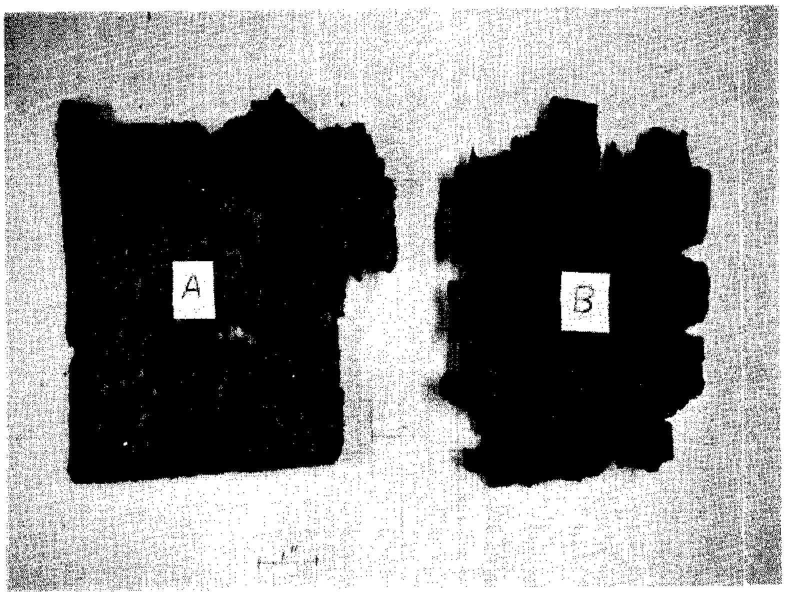


Fig. 8 EXAMPLES OF LARGE BRANDS
A: Wood Shingle
B: 1" Sheathing

V. SUMMARY

The following generalizations drawn from the report are pertinent to the evaluation of the brand producing capabilities of urban areas and to the description of the later stages (transport and host ignition) of brand life.

1) Within the range of induced pressures studied, brands are formed from combustibles that have lost their volatiles and have reached a state of glowing combustion.

2) One inch sheathing produces more and larger brands than 5/16 inch plywood or two inch sheathing. This can be attributed to some degree to the mode of formation. Should the smaller brands prove to be ineffective in spreading fire, this difference will be accentuated.

3) The larger brands from one inch sheathing are generally checkered with deep fissures. The brands thus exist as clustered segments roughly spherical in shape. This would indicate that any increase in the ability of very large brands (greater than about 1-1/2 in.) to ignite hosts is perhaps caused only by their larger area of contact, rather than by greater severity or longer period of burning.

4) Wood shingled roofs (both tight and open sheathing) produce far greater amounts of brands at higher rates than do any bare sheathing or any other combination of sheathing and covering tested.

5) Brand production is greatly increased by high internal pressures associated with wind or the occurrence of a tall fire column below the roof. It is particularly significant that this occurs with built up roofs which are commonly found on large structures. This sensitivity to internal pressure far overshadows the variations produced by the different common asphaltic roof coverings.

6) Addition of an asphaltic covering decreases brand production from one inch sheathing. Intimate contact of the covering (built up roof) decreased brand production at low internal pressures but apparently caused some enhancement at higher internal pressures.

7) Under the range of conditions studied, burning asphalt shingles were found to fly only when fuel was almost exhausted. They were eliminated from further treatment as their effective range was considered to be short, well within the range of fire spread by radiant ignitions.

8) In applying the results presented in Section IV, reasonable approximation should be achieved up to about 0.6 or 0.7 in. H_2O total pressure by linear interpolation along a total pressure scale. It can be noted that buoyancy pressures experienced here were about 75 percent of theorecical under no wind conditions and dropped to about 50 percent of theoretical at wind induced pressures of 0.5 in. H_2O. Similar adjustments should be made for structures having internal subdivision to restrict air flow. Theoretical buoyancy effects (0.011 in. H_2O/ft height) should be used for structures having large undivided volumes. The degree to which wind induced pressure should be applied will definitely require definition of the internal subdivision.

VI. RECOMMENDATIONS FOR FUTURE WORK

OCD is presently pursuing a multiphase program directed at various stages of firebrand life as well as at corollary studies required for background information. At the present writing, the following items appear to be appropriate steps for further study.

A. Definition of Convection Columns

This item was discussed in Section II-B. Let it suffice here to state that more information is needed describing the columns and the aerodynamics of brands within the columns.

B. Firewhirls as Brand Generators

Should firewhirls have high frequency of occurrence, their ability to rend structural combustibles and transport them should be included for study. Experimental treatment in laboratory and field experiments seems appropriate.

C. Evaluation of Internal Building Pressures

More information is needed on the degree to which large structural fires achieve theoretical buoyancy pressures. More information is also needed on the degree to which wind pressures on the building exterior influence internal pressure distribution. Both can and will be incorporated into the goals of the urban burn experiments (work unit 2562A) recently initiated at IITRI. Further information on wind pressures could be measured on large structures without having to burn them and might be considered as a reasonable approach.

D. Brand Generation by Built-Up Roofs

The study reported herein provided a screening of the effects of combinations of roof constructions and internal pressures on brand production. The combinations which appear to require added information are those involving built-up roofs.

In order to derive a general expression for this roof class, a series of experiments is suggested in which covering weight per unit area and sheathing thickness are independently varied for a series of internal pressures. As this type of roof is most common in structures also having large, high, unobstructed interior spaces, the range of internal pressures should extend up to about 1 in. H_2O.